

The binary fraction of the young cluster NGC 1818 in the Large Magellanic Cloud

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ABSTRACT

We use high-resolution *Hubble Space Telescope* imaging observations of the young ($\sim 15 - 25$ Myr) star cluster NGC 1818 in the Large Magellanic Cloud to derive an estimate for the binary fraction of F stars ($1.3 < M_*/M_\odot < 1.6$). This study provides the strongest constraints yet on the binary fraction in a young star cluster in a low-metallicity environment ($[\text{Fe}/\text{H}] \sim -0.4$). Employing artificial star tests, we develop a simplified method which can efficiently measure the probabilities of stellar blends and superpositions from the observed stellar catalogue. We create synthetic colour-magnitude diagrams matching the fundamental parameters of NGC 1818, with different binary fractions and mass ratio distributions. We find that this method is sensitive to binaries with mass ratios, $q \gtrsim 0.4$. We find that, for binaries with F-star primaries and mass ratios $q > 0.4$, the binary fraction is ~ 0.35 . This suggests a total binary fraction for F stars of 0.6 to unity depending on assumptions about the form of the mass ratio distribution at low q .

Key words: methods: statistical – binaries: general – Magellanic Clouds – galaxies: star clusters

1 INTRODUCTION

The majority of stars are thought to form in binary or multiple¹ systems (Goodwin & Kroupa 2005; Duchêne et al. 2007; Goodwin et al. 2007a), and the initial binary properties of stars place important constraints on star formation and the origin of the IMF (Goodwin et al. 2007a; Goodwin et al. 2007b). The majority of stars are also thought to form in star clusters (Lada & Lada 2003), and the binary content of a star cluster plays an important role both in its observational properties and its dynamical evolution (e.g., Kroupa et al. 1999). In addition, many exotic objects observed in star clusters, such as blue stragglers, cataclysmic variables and X-ray sources, are believed to be related to binary systems. Almost all studies of binarity have been limited to nearby solar-metallicity populations. However, it might be expected that metallicity (e.g., through its effects on cooling and hence on the opacity limit for fragmentation) will play a role in the fragmentation of cores to produce binary systems (Bate 2005; Goodwin et al. 2007a).

In general, the most direct way in which to study binary fractions is to examine whether a given star is part of a binary system, on an individual basis. Over the past two decades, the binary fractions of field stars in the solar neighbourhood have been studied carefully in this conventional fashion (e.g., Abt 1983 for B stars; Duquennoy & Mayor 1991 for G dwarfs; Fischer & Marcy 1992 for M-dwarfs; Kouwenhoven et al. 2006 for A and B stars; see also Goodwin et al. 2007a for a review). Nearby clusters and associations have also been examined in detail (see Duchêne 1999 and Duchêne et al. 2007 for reviews and comparisons). However, the binary fractions in more distant, massive clusters have not yet been studied thoroughly, because these environments are too crowded and their distances too great, so that their member stars are too faint to be examined individually for binarity. Fortunately, there is an alternative approach, i.e. by means of an artificial star test technique, which allows us to estimate the binary fractions in crowded environments. By studying the morphology of their colour-magnitude diagrams (CMDs), Rubenstein & Bailyn (1997, hereafter RB97) investigated the binary fraction of main-sequence stars with $15.8 < V < 28.4$ mag in the ~ 13.5 Gyr-old (e.g., Pasquini et al. 2007) post-core collapse Galactic globular cluster NGC 6752. They found a binary fraction of 15–38 per cent in the inner core radius, falling to

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¹ For brevity, by ‘binaries’ we generally also mean ‘multiples’, as many stars are found in triple and higher-order multiple systems. We will distinguish the two only when it is important to do so. Note that the analysis in this paper is of *binary* systems.

Table 1. Fundamental parameters of NGC 1818

Parameter	Value	Ref.
$\log(\text{age yr}^{-1})$	7.2 ± 0.1	2
	$7.4 - 7.6$	5
[Fe/H] (dex)	-0.4	6
$E(B - V)$ (mag)	0.05	4
$(m - M)_0$ (mag)	18.58	1
$\log(t_{\text{rh}} \text{ yr}^{-1})$	$9.0 - 9.7$	7
Mass (M_{\odot})	3×10^4	3

REFERENCES: 1, Castro et al. (2001); 2, de Grijs et al. (2002a); 3, Elson et al. (1987); 4, Hunter et al. (1997); 5, Johnson et al. (2001); 6, Korn et al. (2000); 7, Santiago et al. (2001)

$\lesssim 16$ per cent at larger radii, with a power-law mass ratio distribution. For other old globular clusters, Bellazzini et al. (2002) estimated the binary fraction in NGC 288 for stars with $20 < V < 23$ mag (corresponding to masses of $0.54 \lesssim M_*/M_{\odot} \lesssim 0.77$) at 8–38 per cent within the cluster’s half-mass radius (and at < 0.10 in the outer regions, most likely close to zero), regardless of the actual mass ratio distribution. Zhao & Bailyn (2005) claimed 6–22 per cent of main-sequence binaries ($19.2 \leq m_{\text{F555W}} \leq 21.2$ mag) for M3, within the cluster’s core radius, and between 1 and 3 per cent for stars between 1 and 2 core radii. By applying similar techniques to the post-core-collapse Galactic globular cluster NGC 6397, Cool & Bolton (2002) derived a binary fraction of 3 per cent for main-sequence stars with primary masses between 0.45 and $0.80 M_{\odot}$, for a range of mass ratios. Based on an extrapolation to all mass ratios, they estimated the total main-sequence binary fraction in the cluster core at 5 to 7 per cent. However, all of the clusters thus far studied in this way are old clusters in which dynamical evolution is expected to have significantly altered the initial binary population.

In this paper, we use accurate photometric observations of the young low-metallicity star cluster NGC 1818 in the Large Magellanic Cloud, taken with the Wide Field and Planetary Camera-2 (WFPC2) on board the *Hubble Space Telescope* (*HST*), to study its binary fraction. The photometric data and the cluster CMD are discussed in Section 2. Our newly developed method to correct for stellar blends and superpositions, based on the artificial star test technique, is presented in Section 3. The fitting of the binary fraction is discussed in Section 4, and Section 5 contains a further discussion and our conclusions.

2 THE COLOUR-MAGNITUDE DIAGRAM AND BACKGROUND DECONTAMINATION

Our photometric results were obtained from nineteen WFPC2 observations with the F555W and F814W filters. The data calibration and reduction were performed by Liu et al. (in prep.; see also de Grijs et al. 2002a) using the IRAF APPHOT software package. They also converted the magnitudes in these two filters (in the STMAG system) to the standard Johnson-Cousins V and I photometric system using the transformation coefficients of Holtzman et al. (1995). We show the CMD of NGC 1818 in Fig. 1 (left panel) and provide the current best estimates of a few important param-

eters of this cluster in Table 1. We use the Padova isochrones (Girardi et al. 2000) to perform our fits to the cluster’s CMD.

As noted by Castro et al. (2001), an old red giant population and an intermediate-age red giant clump population are clearly seen in the CMD of NGC 1818. If we adopt an age for this cluster of about 25 Myr (e.g., de Grijs et al. 2002a, and references therein), these older components can only be interpreted as background field stars in the LMC’s disc. Therefore, the main sequence of NGC 1818 is severely contaminated by field stars. Here, we adopt a statistical approach to subtract background stars, which is similar to that adopted by Bonatto et al. (2006). The middle panel of Fig. 1 shows the CMD of the LMC field near NGC 1818. We only remove the stars in the region $19 \leq V \leq 25$ mag and $-0.1 \leq (V - I) \leq 1.5$ mag, since this region contains almost all the stars for which the completeness is greater than 50 per cent. In order to perform the field star decontamination procedure, we divide both the background and the cluster CMDs into grids of cells, in colour and magnitude. We count the number of stars in each cell in the background CMD, and then randomly remove the corresponding number of stars, corrected for the difference in area covered, from the respective cell of the cluster CMD. The right-hand panel of Fig. 1 shows the results of the background decontamination.

3 ARTIFICIAL STAR TESTS

Ideally, if there is no binary population, nor any observational errors, all stars in a cluster should lie on the same isochrone, because they were all born at approximately the same time in the same giant molecular cloud (i.e., they have the same metallicity). However, in Fig. 1 we can clearly see a broadening of the cluster’s main sequence. There are three factors that contribute to this broadening: (i) photometric errors, (ii) superposition effects, and (iii) the presence of true binary and/or multiple systems. The photometric errors broaden the main sequence symmetrically if we assume the magnitude errors to be Gaussian. However, the other two factors skew the stars to the brighter, and redder, side relative to the corresponding best-fitting isochrone. However, it is difficult to distinguish between superpositions and physical binaries on the basis of only CMD morphological analysis. In order to obtain the binary fraction of NGC 1818, we therefore perform Monte Carlo tests, where we produce artificial star catalogues and compare the spread of real and artificial stars around the best-fitting isochrone.

Since the photometric errors of the observed stars strongly depend on their magnitudes and their positions on the *HST*/WFPC2 chips used for the observations, exponential functions were adopted to fit the relation between the magnitude and the standard deviation of the photometric errors (note that these relations vary between the WFPC2 chips). Each artificial star (see below) is randomly assigned Gaussian photometric errors, of which the standard deviations are given by these exponential functions. Fig. 2 shows the relations for V and I for the *HST*/WF3 observations; the centre of the corresponding PC1 chip is located at the half-light radius.

The global stellar mass function of NGC 1818 is found to be well fitted by a Salpeter (1955) power law for masses $> 0.6 M_{\odot}$ (de Grijs et al. 2002b; Kerber et al. 2007). There-

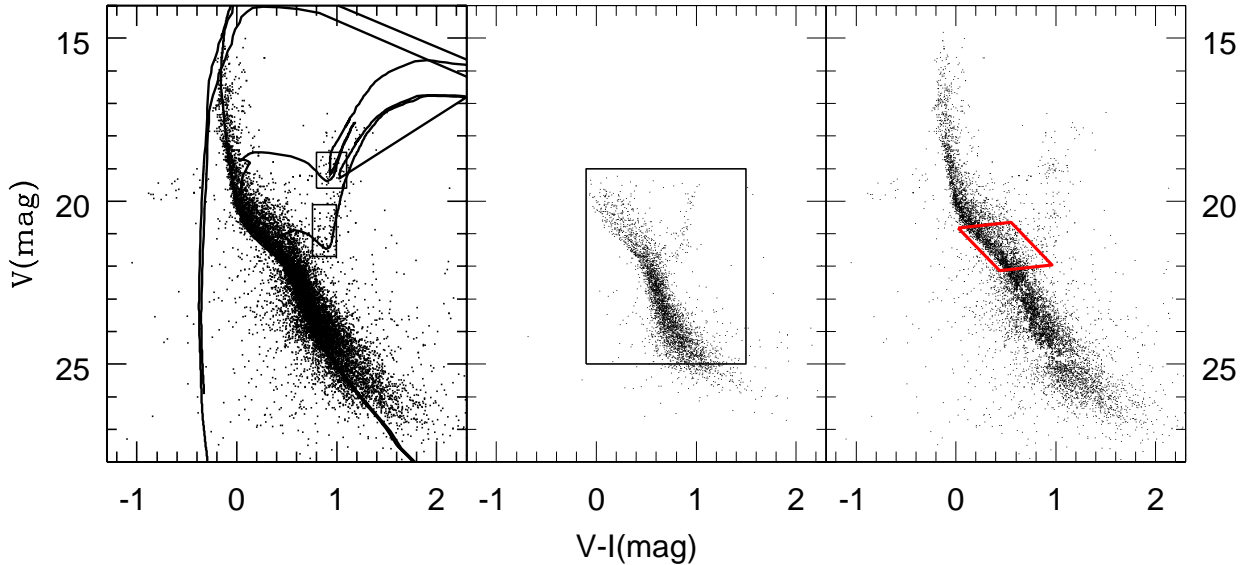


Figure 1. CMDs of NGC 1818 and the background field. The left-hand panel is the original CMD. A 25 Myr isochrone is used to fit the cluster, and two much older, 0.6 Gyr and 2.5 Gyr isochrones to fit the background red clump and red giant stars. All isochrones shown are for a metallicity of $Z = 0.008$ (cf. $Z_{\odot} = 0.019$). The contribution of the background (field) stars at these evolutionary stages is estimated from star counts in the two rectangular boxes shown in this panel (for the upper and lower boxes, respectively). The middle panel shows the CMD of the background field (from which we only use the stars inside the box shown in this panel for the field-star correction done in this paper), and the right-hand panel is the decontaminated CMD of NGC 1818. Our analysis of the binary fraction of NGC 1818 is confined to the stars in the parallelogram indicated in the right-hand panel, which covers stars of masses from 1.3 to $1.6 M_{\odot}$.

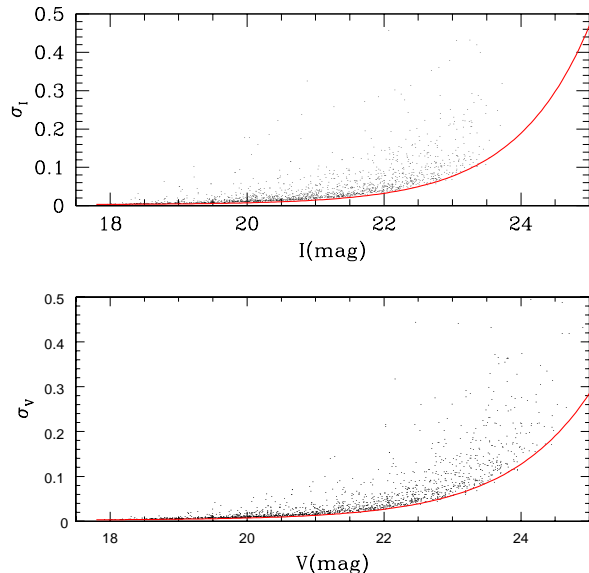


Figure 2. Relations between the standard deviations of the photometric uncertainties and stellar magnitudes for the WF3 chip. The solid lines are the best exponential fits.

fore, we draw the masses of single stars and the primary stars of the binary population from a Salpeter (1955) $\alpha = 2.35$ power-law IMF in the mass range $0.6 \leq M_{\star}/M_{\odot} \leq 6.0$. The masses of the secondaries are drawn from a given mass ratio distribution for all primary masses (we discuss the choice of the mass ratio distribution in detail in the next section).

We note that this produces a *total* IMF (of single stars plus each component of binary systems) which is *not* equal to a Salpeter IMF. However, the deviation from a Salpeter IMF is fairly minor. The alternative is to draw both primary and secondary masses from a Salpeter IMF. However, random pairing is excluded in all observed multiple populations (see, e.g. Duquennoy & Mayor 1991; Fischer & Marcey 1992; Kouwenhoven et al. 2005; Duchêne et al. 2007).

The magnitudes and colours of all artificial stars are then obtained by interpolating from the relevant isochrone. For binary stars we simply add the fluxes of the primaries and secondaries to obtain the magnitudes and colours of the system. The results from this procedure are shown in Fig. 3 (left-hand panel).

The best way to simulate the superposition effect is to add artificial stars to the original images (see details in RB97, and references therein). However, one needs to do this, as well as the subsequent data reduction, hundreds of thousands of times, an incredibly computationally intensive task. As a compromise, we randomly distribute our artificial stars on the spatial distribution diagram of the real stars, as shown in Fig. 4, instead of on the original images. If an artificial star has an angular distance from any real star within 2 pixels (corresponding to the size of our aperture), it is assumed to be ‘blended’. Its new magnitude and colour are re-calculated in the same way as for a binary system. In order to avoid double counting, if the output V -band magnitude of any artificial star is 0.752 mag brighter than its input magnitude (as expected for an equal-mass binary system), we assume that we are dealing with a chance superposition and remove the star from the output catalogue. The CMDs of the artificial stars are shown in Fig. 3.

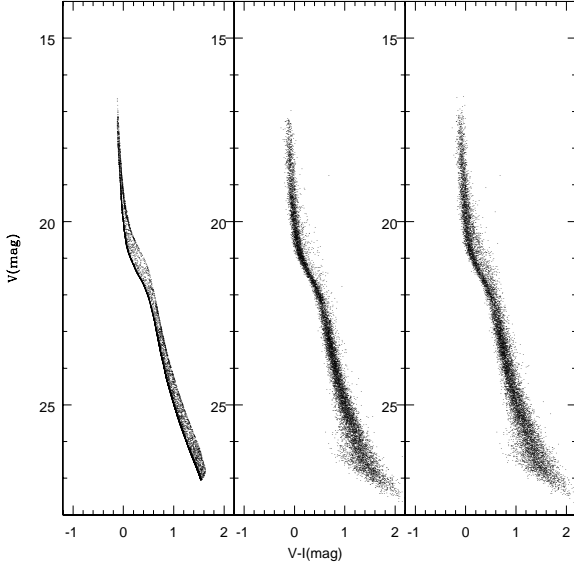


Figure 3. (*left:*) CMD of the artificial stars without the inclusion of errors, and a 50 per cent binary fraction. An equal-mass binary sequence 0.752 mag brighter than the main sequence can be clearly seen. (*Middle:*) CMD of the artificial stars with Gaussian photometric errors, but without any binaries. (*Right:*) CMD of the artificial stars with a 50 per cent binary fraction and Gaussian photometric errors. (Note that without any binaries, a ‘binary sequence’ is also observed in the CMD.)

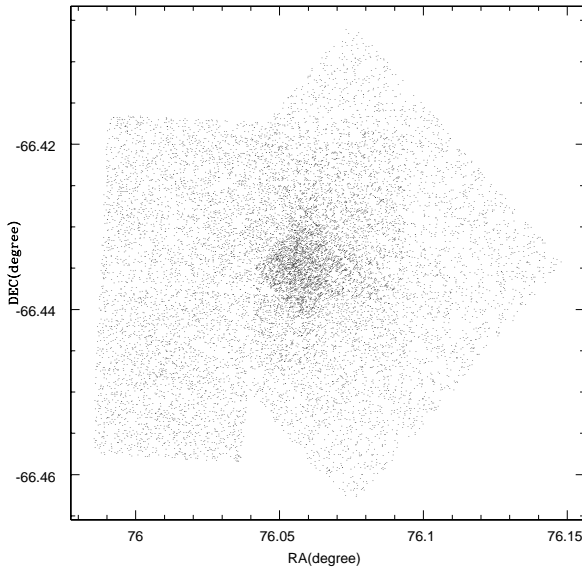


Figure 4. The distribution of photometric point sources in NGC 1818 on which the artificial star catalogues are based (see text). Note the overlap of two WF3 pointings in the centre of the diagram.

For each observed star, we find all artificial stars in the input catalogue that are located within 20 pixels and within 0.2 mag in brightness. We randomly extract one of these artificial stars as the counterpart of the observed star. Finally, we construct a synthetic catalogue containing the same total number of *systems* (be they single stars or unresolved binary systems), a similar luminosity function, projected surface number density and superposition probability as the original data. The only differences between the observed and synthetic catalogues are the binary properties (both the binary fraction and mass ratio distribution).

4 THE BINARY FRACTION OF NGC 1818

We analyse stars in the mass range from 1.3 to 1.6 M_{\odot} (roughly F stars), in the region of the CMD in the parallel-gram shown in the right-hand panel of Fig 1. For brighter stars, the isochrone is almost vertical, and therefore the binary sequence is too close to the main sequence to allow us to distinguish it. (In addition, we are not fully convinced that these bright stars are really main-sequence stars rather than blue stragglers; see Lu et al., in prep.) For fainter stars, the large photometric errors and low completeness make it difficult to detect the binary population. Since the isochrone is almost linear in the region in CMD space of interest, we rotate the ordinates of the artificial and observed CMDs such that the isochrone becomes vertical to a new ‘pseudo-colour’ i.e., a new function of V and $V - I$ produced by rotating the CMD. Note that the exact form of the pseudo-colour function is unimportant.

In Fig. 5 we show the cumulative distribution function (CDF) with pseudo-colour of the true CMD (solid line) and a stellar population with photometric errors, but *no* binaries (dotted line). This is clearly a very bad fit to the data. We also show the best-fit (r.m.s.) binary fraction (f_b), with a uniform q distribution, of $f_b = 0.62 \pm 0.05$ (1σ) (dashed line). Note that the fit is poor at larger pseudo-colours; this is *always* the case and we will discuss this in more detail in Section 4.1.

It is expected that this method will be insensitive to low- q systems in which the secondary contributes very little to the pseudo-colour. In order to test our sensitivity to the mass ratio of a system we produce artificial catalogues that do not include binaries below some mass ratio $q_{\text{cut-off}}$, but contain the same number of binaries above $q_{\text{cut-off}}$. Therefore, to compare with the best-fit $f_b = 0.62$ with $q_{\text{cut-off}} = 0$ (illustrated in Fig. 5), the binary fraction of a catalogue with $q_{\text{cut-off}} = 0.5$ will be $f_b = 0.31$ (the same binary population above $q = 0.5$, and no binaries below).

We find that there is very little difference in the fits to the CDF for $q_{\text{cut-off}} < 0.4$, showing that we are insensitive to binaries with mass ratios less than $q \sim 0.4$. In Fig. 6 we plot the r.m.s. errors of the fits to the observed CDF for a uniform mass ratio distribution with an increasing $q_{\text{cut-off}}$. The error in the fits for $q_{\text{cut-off}} < 0.4$ are dominated by the failure to fit the high pseudo-colour tail of the CDF. However, for $q_{\text{cut-off}} > 0.4$ the error is dominated by a failure to fit the entire CDF, still at high pseudo-colours, but also at low pseudo-colours where intermediate mass-ratio binary systems are no longer included.

This is further illustrated in Fig. 7 where we show

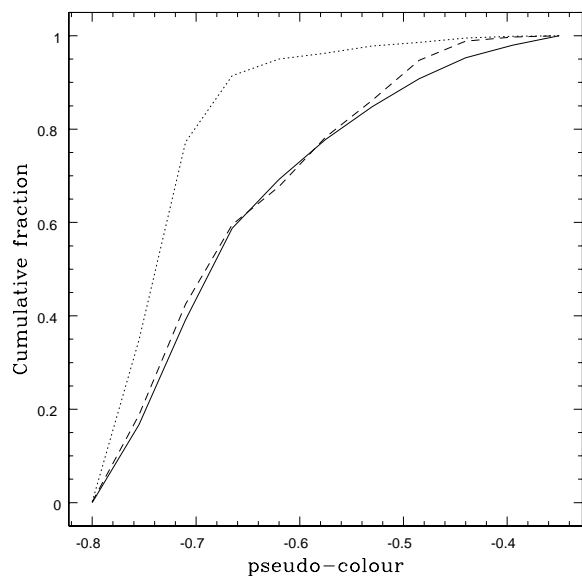


Figure 5. The observed cumulative distribution function with pseudo-colour (solid line) compared with an artificial stellar population with zero binary fraction (dotted line), and the best-fitting (r.m.s.) uniform mass ratio distribution of $f_b = 0.62 \pm 0.05$ (dashed line).

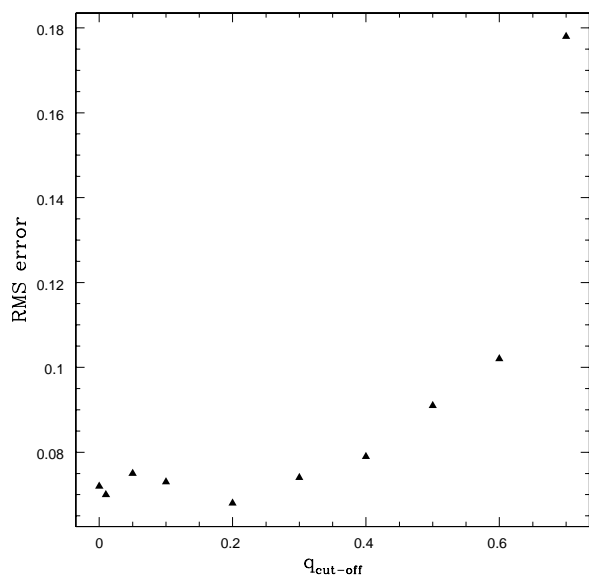


Figure 6. The r.m.s. error of the fit to the observed pseudo-colour cumulative distribution function of a model with a uniform mass ratio distribution with different lower limits to the mass ratio distribution, $q_{\text{cut-off}}$.

the best fits to the CDF for a uniform mass ratio distribution with $q_{\text{cut-off}} = 0, 0.3, 0.4, 0.5, 0.6$ and 0.7 . For these $q_{\text{cut-off}}$ values the best-fitting binary fractions are $f_b = 0.62, 0.42, 0.34, 0.26, 0.20$ and 0.15 , respectively. Given that the best fit to *all* binaries is $f_b = 0.62$ we would expect that, if we were insensitive to binaries with mass ratios below $q_{\text{cut-off}}$ the best-fitting binary fractions would be

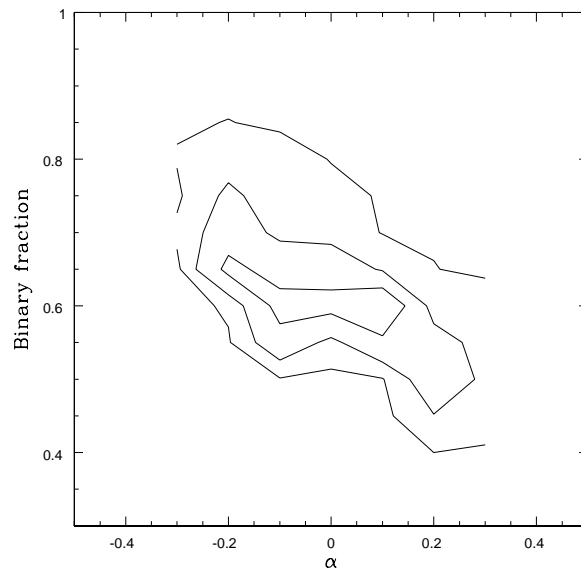


Figure 8. The 1, 2 and 3 σ probability contours of the best-fitting binary fraction f_b and mass ratio distribution q^α for NGC 1818 with no lower limit on the mass ratio distribution (we note that with $q_{\text{cut-off}} \leq 0.4$ the results are essentially identical) The most probable value for the binary fraction is $f_b = 0.62 \pm 0.02$ and the mass ratio distribution is close to flat with $\alpha = 0.0 \pm 0.2$.

$0.62 \times (1 - q_{\text{cut-off}}) = 0.62, 0.43, 0.37, 0.31, 0.25$ and 0.19 , respectively. For $q_{\text{cut-off}} = 0.3$ we recover the expected binary fraction, showing that binaries with $q < 0.3$ do not contribute to the fit. For $q \geq 0.4$ we recover binary fractions that are increasingly below our expectations, illustrating that binaries with $q \geq 0.4$ do indeed contribute to the fit (a fact that is also clear from inspection of Fig. 7 where the poor fits quantified in Fig. 6 are obvious to the eye). Therefore, we adopt a conservative limit on the mass ratios to which we are sensitive, of $q > 0.4$.

In the above discussion we have assumed that the q distribution is flat (at least above $q = 0.4$). This is consistent with the mass ratio distribution of A- and B-type stars in Sco OB2 (Kouwenhoven et al. 2005, their fig. 14). However, G-dwarf mass ratios in the solar neighbourhood are concentrated towards low q (Duquennoy & Mayor 1991). Duquennoy & Mayor (1991) show that the mean local G-dwarf q distribution shows a roughly linear decrease with increasing q for $q > 0.4$ (their fig. 10).

We parameterise the mass ratio distributions as $f(q) \propto q^\alpha$ and examine the parameter space of binary fraction and α to find the best fit to the observed CDF. In fig. 8 we show the probability contours of f_b and α . The best fitting binary fraction is $f_b = 0.60 \pm 0.05$ and is relatively insensitive to α . The form of the mass ratio distribution is close to flat with $\alpha \sim 0$ being the best fit, although the data are consistent with an α between ~ -0.2 and 0.2 . We note that this is somewhat flatter than the $q^{-0.4}$ found by Kouwenhoven et al. (2007) for A- and B-type stars in Sco OB2, although in the range $q = 0.4 - 1$ the Kouwenhoven et al. distribution is consistent with being flat.

The results indicate that the *total* binary fraction of F stars in NGC 1818 is ~ 0.6 with an approximately flat mass

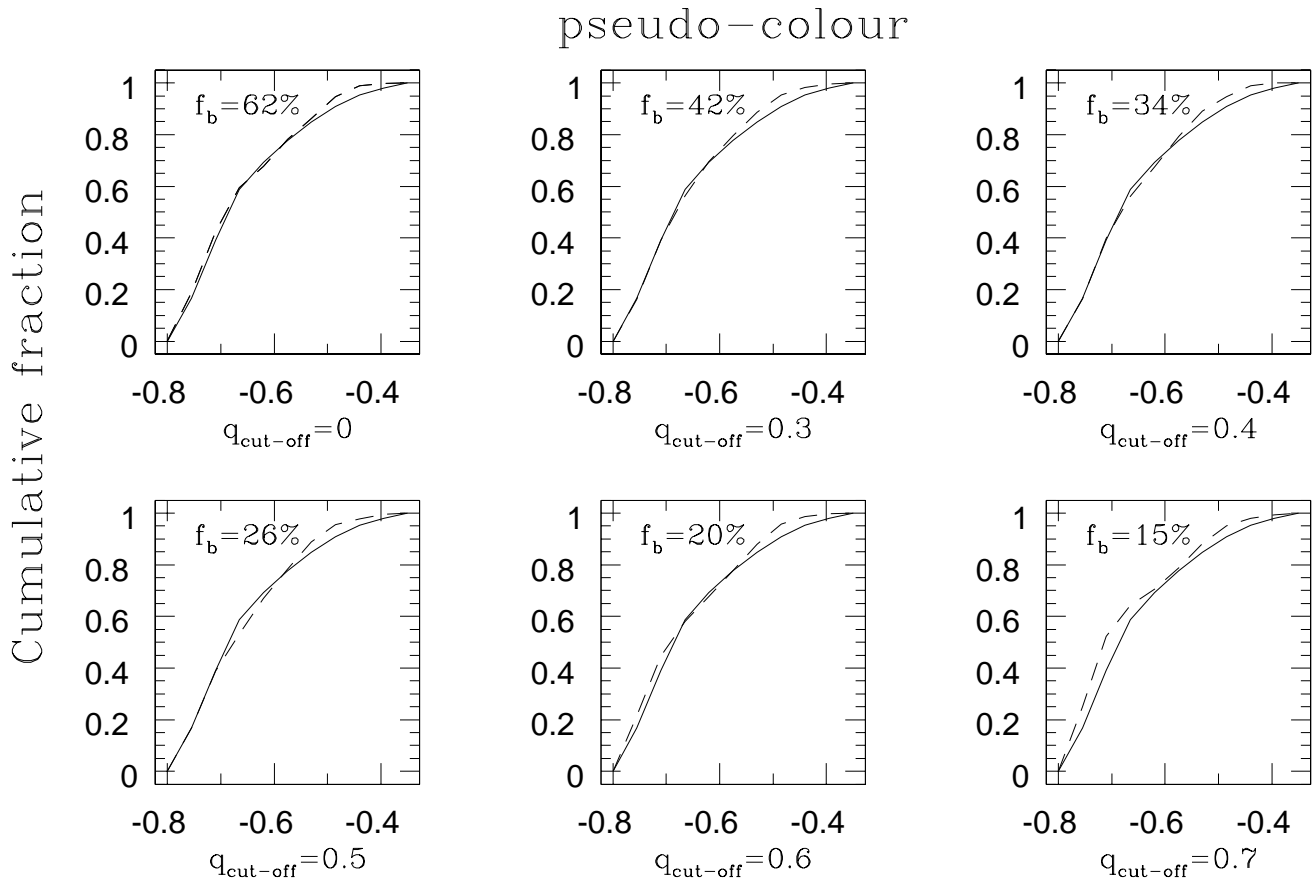


Figure 7. The best fits to the observed CDF for a binary population with a uniform mass ratio distribution and a varying lower limit on the mass ratio, $q_{\text{cut-off}}$. See text for details.

ratio distribution. However, as we are only sensitive to binaries with $q > 0.4$, we may only constrain the binary fraction in this mass range to be $f_{b(q>0.4)} \sim 0.35$. It is impossible to determine the total binary fraction without making some assumptions about the form of the q distribution below 0.4. We feel that it is unlikely that the mass ratio distribution falls below 0.4, meaning that a total binary fraction of ~ 0.6 is probably a safe lower limit (cf. the mass ratio distributions found by Duquennoy & Mayor 1991; Kouwenhoven et al. 2007). *Depending on exactly which assumptions are made for the form of the mass ratio distribution, the total binary fraction ranges from 0.6 to unity.*

4.1 Higher-order multiples in NGC 1818

As noted above, none of the models we have tested are able to fit the CDF above a pseudo-colour of ~ -0.5 . We tested a very wide variety of binary fractions and mass ratio distributions and found that *no* combination of f_b and α were able to fit this region of the CDF. In all cases, the model lies below the observations, showing a dearth of high pseudo-colour systems.

We suspect that this excess of high pseudo-colour systems is due to the presence of higher-order systems than binaries. It is thought that 20 – 30 per cent of multiple systems are triples or higher-order systems (see, e.g. Tokovinin & Smekhov 2002; Correia et al. 2006; as well as Duchêne et

al. 2007 and Goodwin et al. 2007a, and references therein). We will investigate this possibility in more detail in a subsequent paper. However, for now it is interesting to note that our newly developed method is potentially sensitive to higher-order multiple systems.

5 DISCUSSION AND CONCLUSIONS

The CMD of NGC 1818, obtained from *HST* photometry, shows a clearly asymmetric broadening of the main sequence, which implies that this cluster contains a large fraction of binary systems. Using the artificial star test method, we estimate that the binary fraction in the mass range between 1.3 and 1.6 M_\odot is $f_b \sim 0.35$ for systems with an approximately flat mass ratio distribution for $q > 0.4$. This is consistent with a *total* binary fraction of F stars of 0.6 to unity.

Elson et al. (1998) found the fraction of roughly equal-mass ($q \sim 1$) systems in NGC 1818 to be 30 – 40 per cent in the core and 15 – 25 per cent outside the core, which is consistent with our result. We note that our result is quite close to the fraction of binary dwarfs in the field of the same spectral type, which is a little smaller than the fraction in Sco OB2 (Kouwenhoven et al. 2006) and much higher than in Galactic globular clusters (e.g., RB97; Bellazzini et al. 2002).

At 15 – 25 Myr old, NGC 1818 is several crossing times old, and the binary population would be expected to have been modified by dynamical interactions (see Goodwin et al. 2007a, and references therein). In particular, soft (i.e. wide) binaries would be expected to have been destroyed by this age. Therefore, the high binary fraction found for F stars suggests that these binaries are relatively ‘hard’ and able to survive dynamical encounters. The relatively flat mass ratio distribution in NGC 1818 compared to similar mass stars in the loose association Sco OB2 (Kouwenhoven et al. 2007; $\sim q^{-0.4}$) may be evidence for a difference in the initial populations. However, it is more likely to be a product of the different dynamical evolution of the two populations. The larger number of encounters suffered by the binary population in NGC 1818 would be expected to disrupt less bound (i.e. wide and/or low- q) systems, and to form more equal-mass systems leading to a mass ratio distribution more biased to high q .

We conclude that the binary fraction of F stars in the young, low-metallicity LMC cluster NGC 1818 is high and consistent with the field and lower-density clusters. This suggests that, at least among intermediate-mass stars, metallicity down to $[\text{Fe}/\text{H}] \sim -0.4$ does not suppress fragmentation and binary formation, and the binary and higher-order multiplicity of these stars is at least as high as at solar metallicity.

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REFERENCES

- Abt H. A., 1983, *ARA&A*, 21, 343
- Bate M. R., 2005, *MNRAS*, 363, 363
- Bellazzini M., Fusi Pecci F., Messineo M., Monaco L., Rood R. T., 2002, *AJ*, 123, 1509
- 1994, *Galactic Dynamics*, Princeton: Princeton University Press
- Bonatto C., Santos J. F. C., Bica E., 2006, *A&A*, 160, 83
- Castro R., Santiago B. X., Gilmore G. F., Beaulieu S., Johnson R. A., 2001, *MNRAS*, 326, 333
- Cool A. M., Bolton A. S., 2002, in: *A.S.P. Conf. Ser. Vol. 263, Stellar Collisions, Mergers and Their Consequences*, ed. M. M. Shara (San Francisco: ASP), p. 163
- Correia, S., Zinnecker, H., Ratzka, Th., Sterzik, M. F. 2006, *A&A*, 459, 909
- de Grijs R., Johnson R. A., Gilmore G. F., Frayn C. M., 2002a, *MNRAS*, 331, 228
- de Grijs R., Gilmore G. F., Johnson R. A., Mackey A. D., 2002b, *MNRAS*, 331, 245
- Duchêne G., 1999, *A&A*, 341, 547
- Duchêne G., Delgado-Donate E., Haisch K. E., Jr., Loinard L., Rodríguez L. F., 2007, in: *Protostars and Planets V*, B. Reipurth, D. Jewitt, and K. Keil, eds., (Univ. of Arizona Press: Tucson), p. 379
- Duquennoy A., Mayor M., 1991, *A&A*, 248, 485
- Elson R. A. W., Hut P., Inagaki S., 1987, *ARA&A*, 25, 565
- Elson R. A. W., Sigurdsson S., Davies M., Hurley J., Gilmore G., 1998, *MNRAS*, 300, 857
- Fischer D. A., Marcy G. W., 1992, *ApJ*, 396, 178
- Girardi L., Bressan A., Bertelli G., Chiosi C., 2000, *A&AS*, 141, 371
- Goodwin S. P., Kroupa P., 2005, *A&A*, 439, 565
- Goodwin S. P., Kroupa, P., Goodman, A. & Burkert, A. 2007a, in ‘*Protostars and Planets V*’ eds. B. Reipurth, D. Jewitt & K. Keil (University of Arizona Press: Tucson), p. 133
- Goodwin S. P., Nutter, D., Kroupa, P., Ward-Thompson, D. & Whitworth A. P. 2007b, *A&A*, in press
- Hut P., et al., 1992, *PASP*, 104, 981
- Holtzman J. A., Burrows C. J., Casertano S., Hester J. J., Trauger J. T., Waston A. M., Worthey G., 1995, *PASP*, 107, 1065
- Hunter D. A., Light R. M., Holtzman J. A., Lynds R., O’Neil E. J., Jr., Grillmair C. J., 1997, *ApJ*, 478, 124
- Johnson R. A., Beaulieu S. F., Gilmore G. F., Hurley J., Santiago B. X., Tanvir N. R., Elson R. A. W., 2001, *MNRAS*, 324, 367
- Kerber L. O., Santiago B. X., Brocato E., 2007, *A&A*, 462, 139
- Korn A. J., Becker S. R., Gummersbach C. A., Wolf B., 2000, *A&A*, 353, 655
- Kouwenhoven M. B. N., Brown, A. G. A., Zinnecker, H., Kaper, L. Portegies Zwart, S. F., 2005, *A&A*, 430, 137
- Kouwenhoven M. B. N., 2006, Ph.D. Thesis, University of Amsterdam (astro-ph/0610792)
- Kouwenhoven M. B. N., Brown, A. G. A., Portegies Zwart, S. F., Kaper, L. 2007, *A&A*, 474, 77
- Kouwenhoven M. B. N., Brown A. G. A., Zinnecker H., Kaper L., Portegies Zwart S. F., 2005, *A&A*, 430, 137
- Kroupa P., Petr M. G., McCaughrean M. J., 1999, *NewA*, 4, 495
- Lada C. J., Lada E. A., 2003, *ARA&A*, 41, 57
- Pasquini L., Bonifacio P., Randich S., Galli D., Gratton R. G., Wolff B., 2007, *A&A*, 464, 601
- Rubenstein E. P., Bailyn C. D., 1997, *ApJ*, 474, 701 (RB97)
- Salpeter E. E., 1955, *ApJ*, 121, 161
- Santiago B., Beaulieu S., Johnson R., Gilmore G. F., 2001, *A&A*, 369, 74
- Tokovinin, A. A., Smekhov, M. G. 2002, *A&A*, 382, 118
- Zhao B., Bailyn C. D. 2005, *AJ*, 129, 1934